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Modeling Global Positioning System Effects in the TLC/NLC Model

Patrick D. Allen

Project AIR FORCE
Arroyo Center

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Prepared for the United States Air Force United States Army

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Project AIR FORCE
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Preface

This report presents a design for representing the key issues and operational effects of the Global Positioning System (GPS) in the theater-level combat or nonlinear combat (TLC/NLC) model, and possibly in other models as well. This design should be useful to individuals interested in the design and use of space models and theater- or operational-level combat models.

The task was performed in support of RAND's Command, Control, Communications and Intelligence (C3I) projects, and was jointly sponsored by the U.S. Air Force XOXP (Strategic Plans) and the U.S. Army, Deputy Chief of Staff for Operations and Plans. This task was conducted jointly under the C3I/Space Project of the Force Modernization and Employment Program of Project AIR FORCE, and by the C3I/Space for Contingency Operations Project of the Force Development and Technology Program of the Army Research Division's Arroyo Center. Project AIR FORCE and the Arroyo Center are two of RAND's federally funded research and development centers.

Contents

Figures

Tables

Summary

Background

In this time of reduced budgets, military systems need to justify their costs in terms of their contribution to conflict resolution. Unfortunately, the contributions made by support systems, such as the Global Positioning System (GPS), are more difficult to quantify than those of lethal systems. As a result, most combat models find it difficult to represent credibly the benefits of support systems. Although there are many technical models of GPS, few (if any) operational models have attempted to incorporate the GPS effects in terms of how it affects the outcome of battles.

Purpose

This report has two purposes. Its primary purpose is to present a model design for representing the effects of GPS in support of military operations.[1] A secondary purpose is to act as a primer for audiences not familiar with GPS. The purpose of the *design* is to provide a simple, efficient, yet comprehensive representation of GPS support of military operations for use in the theater-level combat or nonlinear combat (TLC/NLC) model at RAND, and possibly in other models. The purpose of the TLC/NLC *model* at RAND is to support policy-level analysis of military operations.[2]

What GPS Is, How It Works, and Our Approach to Modeling It

Technically, GPS is "a space-based radiopositioning and time-transfer system" (ARINC, 1991). Described more simply, it is a constellation of satellites that can provide location data of varying degrees of accuracy to anyone with an

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[1]An early draft of this report was circulated for review by a variety of offices. Review comments were received from the personnel and offices listed in the Acknowledgments, and most of the comments were incorporated into this report.

[2]The TLC/NLC model or modeling tool kit is a prototype for a combat simulation being developed at RAND to improve air and land combat simulation at the operational and theater level. Questions or comments may be directed to the author, Patrick Allen, or to Richard Hillestad, head of the TLC/NLC model development project.

appropriate GPS receiver. The satellites emit a series of precise time signals. The receiver translates the signals from several satellites (normally four) into location data.

This report presents an approach to representing the effects of GPS in support of military air and ground operations at an operational or theater level of aggregation in support of policy-level analysis. We focus on the TLC/NLC model, and its characteristics shape our model design. The level of aggregation in TLC/NLC is flights of aircraft in the air model and battalion-sized combat units in the ground model. Although individual platforms (e.g., number of planes or tanks) are tracked in each flight or unit, the model does not track precise location, orientation, or formation. Both air and ground units follow user-defined networks, which may differ for air and ground and for Blue and Red. Interactions between assets on each network are based on distance from center of flight or unit rather than on sharing the same network.[3]

Based on this level of aggregation in the TLC/NLC model, the design represents the *aggregate* effects provided by GPS support. Given this aggregate level of resolution, it is unnecessary to include in the model the explicit GPS constellation over time or its exact location determination algorithms. Therefore, we use approximate values for location accuracy consistent with the location accuracy available in the model.

To facilitate the presentation of our design, we divide it into four main areas: representing GPS coverage, GPS-equipped assets, the effects of GPS support to GPS-equipped assets, and the representation of countermeasures and counter-countermeasures.

GPS Coverage

For purposes here, we define GPS coverage as *a specified location accuracy given the type of GPS use.* We plan to represent three types of GPS coverage in the TLC/NLC model: absolute, differential, and relative targeting. We also distinguish between relative GPS targeting and the use of GPS in offset targeting.

[3] A slightly more detailed description of the TLC/NLC model is provided in Section 1. See the Bibliography for other documents that provide a more detailed description of the TLC/NLC model.

Representing Absolute GPS Coverage

Absolute GPS coverage is the term applied to normal GPS positioning and navigation transmissions.[4] Both military and civilian users have access to the GPS system, although the accuracy of the data available to them varies. The model design includes the three different degrees of accuracy available to each type of user:

- P-code (10–16 meter SEP,[5] available to U.S. military and other authorized users)
- Civilian access (C/A) code without selective availability (S/A) turned on (20–30 meter SEP)
- C/A code with S/A turned on (54–76 meter SEP).

Selective availability is an intentional distortion of the location data transmitted by the satellites to reduce the location accuracy available to other than U.S. military users. Selective availability can be set for a wide range of degradation, but for purposes of analysis we limit it to being on or off.

The representation of absolute GPS coverage in a theater of operations will be defined by a variable called "GPS state" that defines the effective number of satellites in a good geometry available for determining location accuracy.[6] A GPS state of four or more means that the receiver can obtain good three-dimensional location accuracy (since the time dimension is used to synchronize the signals from each satellite). A GPS state of three means that the receiver loses one dimension, such as the time dimension or the vertical dimension, which may still allow the receiver to obtain good two-dimensional location.[7] GPS states of less than three provide only two dimensions, and thus poor location accuracy. The degree of access by type of user (P-code, C/A code, with or without S/A) determines the possible location accuracy as a function of GPS state.

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[4]A single receiver determining its own location using absolute GPS transmissions is called a "point solution," in contrast to the relative and network solution methods described below.

[5]SEP stands for spheroidal error probable. The SEP values are based on published GPS requirements, while the lower SEP values are the accuracies usually obtained in practice. See the main text for further discussions of the accuracy calculations.

[6]In this report, GPS state refers to the observability state, which is the number of satellites that can be observed by the receiver at a given time. This is not to be confused with the acquisition or tracking state of GPS receivers. The phrase "good geometry" means that the satellites are distributed to provide the receiver with good triangulation and therefore a low geometric dilution of precision (GDOP) (i.e., good location accuracy).

[7]One can also obtain good three-dimensional location accuracy with a GPS state of three when the user has an accurate clock. This is not the case for the majority of users.

Representing Differential GPS Coverage

Differential GPS coverage can increase the receiver's location accuracy and eliminate most of the effects of selective availability. A differential GPS transmitter gathers absolute GPS transmissions over time, and then transmits "corrections" to other GPS receivers to improve their location accuracy. The location error tends to increase approximately linearly with distance from the differential GPS transmitter. A C/A code receiver using differential GPS transmissions can obtain better location accuracy than can a P-code receiver using only absolute GPS transmissions. This is true whether or not selective availability is on, beca_ _ differential GPS eliminates most of the distortion added by selective availability. Since the state of the art of differential GPS is rapidly changing, we included various options for differential GPS, depending on the analyst's assumptions regarding what types of differential technology will be available.

Initially, a differential GPS transmitter would send coordinate corrections to local receivers in line-of-sight or within relay range up to a maximum range of about 300–350 kilometers. Beyond that range, the differential GPS transmitter and the receivers no longer share the same four GPS satellites, a prerequisite for the coordinate correction type of differential GPS operations. This procedure is known as the "relative solution" method of location determination, since the accuracy is determined relative to another GPS receiver. We model this type of differential GPS coverage as additional regions centered on the stationary differential GPS transmitter. Properly equipped assets within those regions benefit from improved location accuracy.

There are also wide-area differential GPS alternatives in various stages of development. Wide-area or "network solution" differential GPS methods transmit error correction data *for each satellite*, thereby precluding the necessity to share the same four satellites. For example, INMARSAT has suggested a wide-area differential GPS network based on their satellites in geosynchronous orbit. To represent any kind of wide-area differential GPS in the TLC/NLC model, we simply eliminate the maximum range restriction of 300–350 km and allow assets *within* the theater or affected region to benefit from differential GPS transmissions.

Representing Relative GPS Targeting

In relative GPS targeting, a GPS-equipped launcher and a GPS-equipped munition share location data so that the munition may be guided to the target

more accurately. Like the coordinate correction differential GPS method, relative GPS targeting must share the same four GPS satellites, thereby limiting the useful range of relative GPS targeting to about 300–350 km or a munition flight time of less than 15 minutes. The representation of relative GPS targeting in the TLC/NLC model will be a function of the capabilities of the sensor, the launching platform, and the munition. If the proper conditions are met, the accuracy of the munition will be improved.

Offset Targeting Using GPS

In offset targeting, the location of the target is not known, but its location relative to a reference point is. The accuracy of the reference point location determines the relative location accuracy of the target. Using GPS to locate the reference point more accurately provides better target location. The location of the reference point can be refined either by placing a GPS receiver on it or (less accurately) by determining the location of the reference point at a distance by a sensor on a GPS-equipped platform.

GPS-Equipped Assets and Prerequisites for GPS Benefits

Users can directly benefit from GPS transmissions only if two prerequisites are met:[8] The user must have GPS equipment and a relatively clear line-of-sight between the receiver and the satellites. GPS-equipment for absolute and differential GPS comes in six main categories, in order of decreasing location accuracy:

- P-code with wide-area differential access
- C/A code with wide-area differential access
- P-code with coordinate correction differential access
- C/A code with coordinate correction differential access
- P-code without differential access
- C/A code without differential access.

[8]Assets not equipped with GPS can benefit from being in proximity to GPS-equipped assets. Since TLC/NLC only operates flights of aircraft or ground maneuver battalions, the issue of equipping only selected assets with GPS becomes moot. As long as key elements are considered GPS-equipped in TLC/NLC, the flight or unit is considered to benefit from GPS.

In TLC/NLC, objects representing aircraft and other platforms are assigned one of the six categories of GPS access (or no access). Similar attributes are defined for relative GPS targeting. If an asset is GPS-equipped, then the combination of the GPS state and the type of access determine the base location accuracy. The presence of selective availability may degrade C/A code access of absolute GPS transmissions.

Two additional location degradations require consideration. First, differential GPS location accuracy degrades as a function of distance from differential GPS transmitter by about one meter SEP for every 80 km. Exceeding 300–350 km precludes the use of coordinate correction differential GPS, but will not limit wide-area differential GPS. Second, relative GPS targeting depends on the GPS receiver and the accuracy of the sensor on the platform.

Another prerequisite for GPS use is a line-of-sight clear of heavy foliage between the receiver and the satellites. The relatively weak GPS signal attenuates rapidly in foliage, and therefore is less useful in forested or jungle environments. The Army is developing mechanisms for extending the GPS antenna above the foliage, but the aggregate effect is that GPS support is not continuous in environments with heavy foliage. Discontinuous GPS support will make location determination more difficult in a jamming environment, as described in the section on GPS countermeasures and counter-countermeasures.

Effects of GPS Transmissions on GPS-Equipped Assets

This model design incorporates three main GPS benefits: improved self-location accuracy, increased target location accuracy, and stand-off munition launch. These benefits tend to be independent of darkness and relatively insensitive to the effects of weather.[9]

Benefits of Improved Self-Location Accuracy

Improved self-location offers two main benefits: improved navigation and reduced fratricide. Improved navigation can increase the effectiveness and survivability of land, sea, and air platforms. The reasons can range from not getting lost to avoiding the enemy. Improved self-location accuracy can also assist search and rescue operations, special forces operations, and artillery

[9]The only environmental effects that affect GPS signals are ionospheric and tropospheric disturbances, neither of which is represented in TLC/NLC. The effects of such disturbances on the GPS state should be calculated off-line.

battery positioning. For example, the more accurately and quickly an artillery battery can determine its own location, the more accurate will be its fires. The design presents several options for representing these benefits (or representing penalties of not having these capabilities) in the TLC/NLC model.

Reduced fratricide results from better knowledge of friendly locations relative to each other (assuming command, control, communications and procedures that can use this location information to preclude fratricide). For example, indirect fire fratricide incidents during Operation Desert Storm were well below historical rates, and GPS helped keep the rate low with improved location accuracy and reporting.[10]

Benefits of Improved Target Location Accuracy

This benefit has three aspects: increased lethality against fixed and mobile targets, faster production of accurate target location data, and the opportunity for additional platforms to designate targets.

Better target location allows platforms to deliver their munitions more accurately. Moreover, GPS-equipped munitions may be able to improve their lethality through improved target location accuracy. Increased target location accuracy will reflect in TLC/NLC as a higher probability of hit, depending on the type of platform, munition, and target.[11]

An added benefit to better target location is a possible reduction in munitions expended as a hedge against target location uncertainty. This benefit applies both to air-launched stand-off munitions and ground-launched indirect fire munitions, such as artillery and surface-to-surface missiles.

Faster production of target and fires location data means a faster response time to engage targets. This is especially useful against fleeting targets, such as mobile tactical ballistic missiles. Relative GPS could decrease the time required to produce useful pictures of the battlefield and the potential targets within the field of view. In TLC/NLC, faster production times means a higher probability of engagement against time-sensitive targets.

Additional platforms that can provide target designations range from airborne sensors (such as J-STARS and ASARS) to special forces teams on the ground. For

[10] From the transcript of a taped interview with the combatants at the battle of 73 Easting, Operation Desert Storm.

[11] In TLC/NLC, there are factors besides these three that modify the effectiveness of munitions, such as weather, terrain, and the availability of intelligence assets, such as J-STARS.

example, a special forces team can reconnoiter the target site and report its location accurately using hand-held GPS equipment. Sensors and platforms not traditionally used for accurate target designation can provide more accurate target location data through the use of GPS equipment. In TLC/NLC, this target location accuracy improvement is provided as a function of the type of sensor or platform and the type of target.

Benefits of Stand-Off Munitions Launch

Stand-off launch offers two benefits: reduced vulnerability to enemy threats and reduced flight time to engage targets, which could save fuel, time, and sorties. GPS-equipped munitions allow strikes from much farther away than in the past because of the increased accuracy of the munition and the target location. Munition launch can occur at a range beyond many enemy air defense threats, especially terminal air defense systems. Also, the ability to engage multiple targets from a single launch point means that fewer stand-off sorties will be required to engage the same number of targets as traditional penetrating sorties. For these two reasons, the survivability of GPS-platforms will increase in TLC/NLC.

Similarly, an increased stand-off range will allow a platform to perform its mission within reduced flight times, saving both fuel and time. The reduction in time results not only from the shorter flight time to reach a stand-off release point, but also from the ability of the platform to engage multiple targets from a single stand-off launch point. TLC/NLC represented this benefit by lower fuel consumption rates and higher average daily sortie rates.[12]

GPS Countermeasures and Counter-Countermeasures

The countermeasures against GPS-equipped assets, and the counters to these countermeasures, are divided into three areas: direct threats against GPS transmitters, receivers, and signals.[13]

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[12]This assumes that the time required to service, replan, and relaunch an aircraft is constant. A shorter flight time per sortie means that more sorties can be launched per day given the same amount of time spent on the ground.

[13]Note that this design generally assumes a nonnuclear threat environment. If nuclear weapons are used to destroy GPS satellites or to disrupt GPS transmissions in the scenario, apply off-line GPS state calculations to determine effective GPS state over time.

Direct Threats Against GPS Transmitters

Today, few credible threats menace GPS satellites. Although the model design includes the option of analyzing threats against GPS satellites through reduced GPS states, such threats are unlikely. Direct threats against differential GPS transmitters are more likely, although a probable and effective countermeasure is proliferation. Large fields of differential GPS transmitters would be difficult to neutralize.

Direct Threats Against GPS Receivers

Since GPS receivers tend to be integrated into a platform or munition, destroying a GPS receiver will probably destroy the platform as well. Therefore, direct threats against GPS receivers will be represented in TLC/NLC in the same way as any other threat against the platform.

Direct Threats Against GPS Signals

There are two main threats against GPS signals: jamming and spoofing. Jamming is by far the most effective and most likely threat against the use of GPS-equipped assets for targeting purposes. The GPS navigation signal is weak and susceptible to jamming. It also takes less jamming power to preclude the receiver's acquisition of the GPS signal than to break the lock of an acquired signal.

The most effective type of jammer against the GPS signal is a wide-frequency-band jammer. Even a relatively low-power (10 watt) jammer is effective at 40 km range against C/A code GPS. However, the jammer has to radiate almost continuously to be effective in this mode. An effective counter-countermeasure is to destroy the jamming transmitter. However, if there are a large number of low-power jammers in action in the same area, destroying the field of jammers will not be cost effective.[14] The use of inertial navigation systems (INS) for terminal guidance in the final approach will help counter the GPS jamming threat up to a point.

An opponent can engage in spoofing by sending a false message to a GPS receiver to direct the receiver's platform off course. The encrypted P-code is

[14]Conversely, it may not be cost effective for the enemy to proliferate GPS jammers to deny our GPS access when compared to the opportunity cost of forgoing additional military capability for their side.

called the Y-code, and is extremely difficult to spoof. Since spoofing GPS signals is difficult to accomplish in practice, we have simply included spoofing as another form of jamming in TLC/NLC.

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Acronyms and Abbreviations

Absolute GPS	Basic or normal GPS transmissions
ARPA	Advanced Research Projects Agency
ASARS	Advanced synthetic aperture radar system
ASAT	Antisatellite
ATCAL	Attrition calibration methodology
CADEM	Calibrated differential equation methodology
CEP	Circular error probable
dB	Decibel
Differential GPS	GPS location correction signal
GDOP	Geometric dilution of precision
GLONASS	Global navigation satellite system (the GPS equivalent of the former USSR)
GPS	Global Positioning System
HUMINT	Human intelligence
INMARSAT	International Marine Satellite
INS	Inertial navigation system
J-STARS	Joint surveillance target acquisition radar
MTI	Moving target indicator
PPS	Precise positioning service
Relative GPS targeting	GPS-assisted method to improve munition delivery to a target
S/A	Selective availability
SAR	Synthetic aperture radar
SEP	Spheroidal error probable
SOF	Special operations forces
SPS	Standard positioning service
TLC/NLC	Theater-level combat or nonlinear combat model
TR-1	Airborne surveillance platform
2 drms	Twice the distance root mean square

1. Introduction

Background

In the face of recent and projected budget reductions, all military systems will need to justify their costs in terms of their benefits as measured by their contribution to conflict resolution. Most lethal systems have relatively quantifiable measures of effectiveness, such as a probability of kill or an exchange ratio. Support systems, such as the Global Positioning System (GPS), do not yet have an accepted set of measures of effectiveness in terms of their contribution to warfighting outcome. As a result, most analysis approaches and combat models find it difficult to credibly represent the benefits of support systems. GPS transmissions can enhance the navigation of land, naval, and aerial platforms, and might be useful for the guidance of certain types of munitions, such as cruise missiles. The first question is how to quantify the benefits of nonlethal support systems, such as GPS, and second, how to model the benefits in combat models.

Purpose

The primary purpose of this *document* is to describe a model design for representing the effects of GPS assets in support of military operations. A secondary purpose is to serve as a primer for audiences not familiar with GPS, while avoiding as many GPS-unique terms as possible, such as the geometric dilution of precision (GDOP). The purpose of this *design* is to provide a simple yet effective representation of GPS operations in support of military operations for use in RAND's theater-level combat or nonlinear combat (TLC/NLC) model, and possibly in other models as well. The purpose of the TLC/NLC *model* at RAND supports policy-level analysis of military operations.[1]

[1]"The TLC/NLC modeling tool kit is a prototype for a combat simulation model being developed in a research effort at RAND to improve air and land combat simulation at the operational and theater level. . . . The impact of dramatic changes in the political-military environment, the need to treat more explicitly the large uncertainties present in today's analytic environment, and an opportunity to capitalize on new methodological, software, and hardware developments have all provided an impetus to the research on TLC/NLC. The major design goals for the model include the capability for analyst operation via an intuitive graphical user interface, facilities for incorporating input from database management systems, tools for managing multiple simulation runs and other application software for further analysis and display." From Hillestad et al., forthcoming, pp. iii and xiii.

Objectives

This report has four objectives: first, to identify and describe the key features of GPS operations to be represented in the model design; second, to describe and justify the simplifying assumptions and key parameters necessary to design a simple model of these features; third, to describe the model design itself, including the parameters and the data for the parameters, in sufficient detail to encourage rapid implementation in the TLC/NLC model; and fourth, to act as a mechanism for continuing review and feedback by the analytic community to ensure that the design is up-to-date with the latest GPS advances and that the design remains adequate for our purposes. Please direct your comments, questions, and suggestions to the author, or to Richard Hillestad, head of the TLC/NLC model development project.

Approach and Organization

There are many technical models of GPS, but few, if any, combat models have attempted to incorporate the effects of GPS support to air and ground forces in terms of warfighting outcome. This report describes a way to represent the effects of GPS in support of military air and ground operations at an operational- or theater-level of aggregation for policy-level analysis.

The TLC/NLC model under development at RAND is an operational-level or theater-level model of air and land operations. To support rapid, multiscenario analysis with extensive sensitivity analysis, the TLC/NLC model must focus on breadth rather than on elaborate detail. As a result, a design of GPS operations and their effects on land and air combat in the TLC/NLC model must concentrate on the key operational issues, rather than on details such as dynamic line-of-sight calculations. For example, if we were to model the orbit of each GPS satellite and the line-of-sight to each receiver within the TLC/NLC model, the model's run time would increase by a factor of four or more.[2]

The primary design factor is the level of resolution in the TLC/NLC model. The level of aggregation in the TLC/NLC model is flights of aircraft in the air model and battalion-sized combat units in the ground model. Although the *quantity* of individual aircraft and vehicles are tracked in each flight and maneuver battalion, the precise location, orientation, or formation of these assets within their flight or unit is not tracked. Therefore, location accuracy in the model is

[2]This estimate is based on years of experience and numerous cases in which an operational combat model incorporates a detailed model of one system or functional area. In some cases, a factor of four increase is a conservative estimate.

limited to those cases where a difference in location accuracy will make a difference in a TLC/NLC assessment process (such as movement and combat).

TLC/NLC is a network-based model. Both air and ground units follow user-defined networks that may differ for air and ground, and for Blue and Red. Interactions between assets on each network are based on distance from center of flight or unit rather than on sharing the same network (see Figures 1 and 2).

Figure 1 shows an air network passing through various detection bands and engagement zones. An aircraft that crosses a detection band may or may not be detected depending on a variety of factors. Similarly, engagement by surface-to-air missiles, antiaircraft artillery, or enemy aircraft may or may not occur at various points along the air network. There may be many such engagement zones entered during a raid, depending on the situation. Targets are attacked when surviving aircraft reach designated launch points.

Figure 2 shows sample ground networks for Red and Blue, how they relate to each other, and how they relate to one of the air networks. When ground units are in engagement range (which varies by weapon holding), the assets of the unit may engage enemy assets in opposing units. Similarly, aircraft that reach weapons release points in the model will affect ground targets within range. One

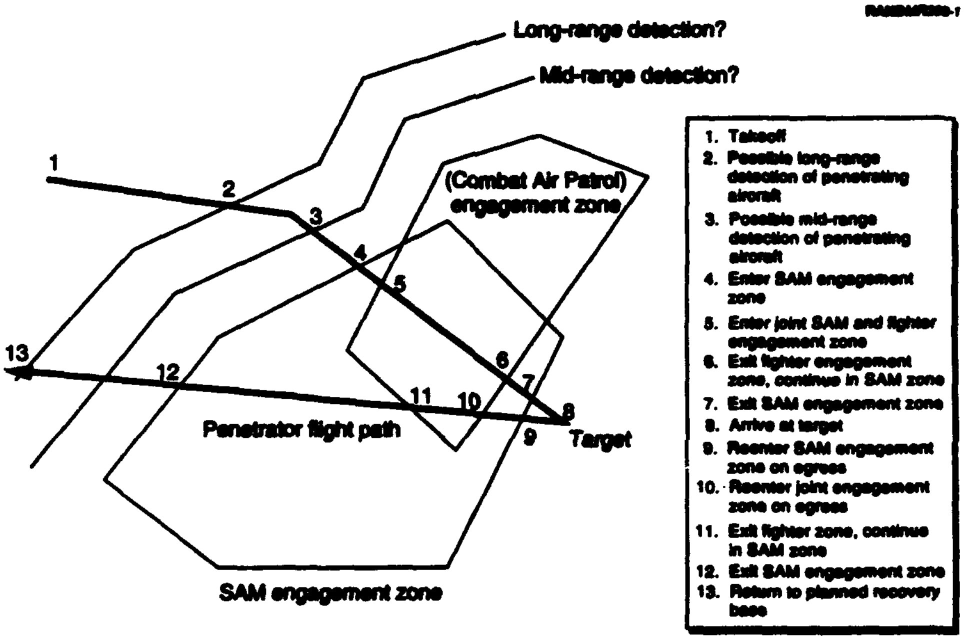

Figure 1—Example of Determining Sequence of Engagements

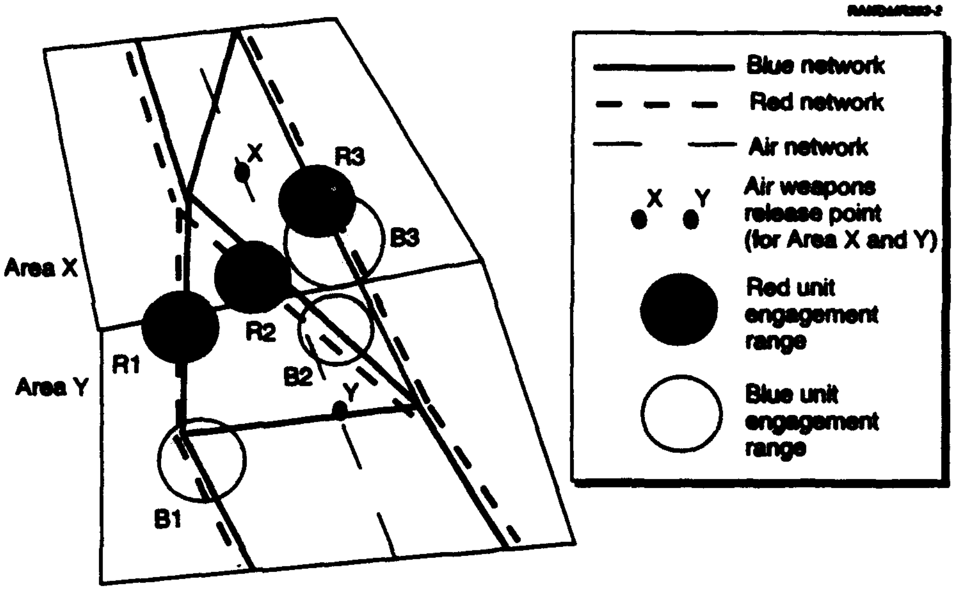

Figure 2—Example of Ground Network Interactions

launch release point is usually used to assess attacks against multiple points. Note that the path of a penetrating aircraft that would overfly the target is not explicitly represented in the model, but the effects of terminal air defenses against the attacking aircraft are represented.

Owing to the relatively aggregate level of resolution in the TLC/NLC model, calculating the exact location of individual assets to tenths of meters is not appropriate. Although air-to-ground munition accuracies in the model care whether the accuracy is to 3 meters or 10 meters spheroidal error probable (SEP), the model does not care if the accuracy is 2.5 meters versus 2.7 meters. It simply does not matter in the model. Although in some cases this report defines levels of accuracy down to tenths of meters for comparison between types of GPS support, the actual implementation in the model will probably be in broad categories of accuracy. For example, the model might distinguish between 3-meter-or-less accuracy provided by differential GPS, 10-meter-or-less accuracy provided by standard military location accuracy, and 50-meter-or-less accuracy provided by civilian access to GPS (under appropriate conditions), but the model is not likely to distinguish between increments of 1 meter accuracy or less.[3]

[3]In a real-world operational setting, the location accuracy values may vary even more widely than described here because of variations in the type and quality of receiver, the relative geometry between the satellites and the receivers, and tropospheric or ionospheric disturbances. However, the range of approximate values given here is designed to support aggregate-level analysis, and not to support the navigation of individual systems in real time.

There are very accurate simulations of GPS satellite orbits over time and the resulting coverage at various places on the globe over time, and such models should be used when attempting to address issues related to the details of specific GPS operations. In contrast, the TLC/NLC model is designed to focus on the *aggregate effects* of GPS support to military operations, rather than be a detailed simulation of GPS satellite and receiver operations.

To maintain and express a simple design, we divided GPS operations and effects into four main subjects: GPS coverage, GPS-equipped assets, the effects of GPS transmissions on GPS-equipped assets, and GPS countermeasures and counter-countermeasures. Section 2 describes GPS coverage—how well the GPS satellites can provide location accuracy to various users of normal or absolute GPS, differential GPS, and relative GPS targeting techniques. A representation of selective availability (S/A) on GPS transmissions is also included. Section 3 describes the representation of GPS-equipped assets and their efficient representation in the model. Section 4 describes the effects of absolute, differential, and relative GPS techniques on appropriately equipped airborne and terrestrial receivers. The last section presents a simple representation of various kinds of GPS countermeasures and counter-countermeasures.

2. GPS Coverage

"GPS is a space-based radiopositioning and time-transfer system" (ARINC, 1991). Since GPS transmissions cover the Earth, GPS coverage is considered global. However, in this report, we will define GPS coverage as *a specified location accuracy given the type of GPS use.* We plan to represent three types of GPS coverage in the TLC/NLC model: absolute coverage, differential coverage, and relative targeting procedures. We also distinguish between relative targeting and offset targeting, since the two concepts are similar. The definition and distinctions of each type of coverage will be described in the following subsections.

Representing Absolute GPS Coverage

Absolute GPS coverage comes in two forms of access: military (also called precise positioning service or PPS) and civilian (also called standard positioning service or SPS). Military access to the GPS transmissions provides the best accuracy to determine a platform's velocity (to 0.2 knots) and location in four dimensions (latitude, longitude, elevation, and time). As long as the platform with a GPS receiver has line-of-sight access to four or more GPS satellites in a favorable geometry,[1] the receiver will be able to determine its three-dimensional (3-D) location to about 10–16 meters SEP.[2] Owing to the orbital configuration of

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[1]GPS location accuracy is dependent upon the geometry of the satellites compared to each other and the receiver location. The geometric dilution of precision (GDOP) is the measure used to determine good geometry and the resulting location accuracy. To use a layman's example, the location of an object 1000 meters away is difficult to determine using triangulation when being observed from two points only 10 meters apart. If the two observation points are 500 meters apart, the location accuracy of the distant object is much more accurately determined. Similarly, if four satellites provide triangulation through good geometry to the receiver, the 3-D location accuracy of the receiver will be good. If only three satellites are available, then the receiver's 2-D location accuracy will be good, unless the receiver also has an accurate clock. With a precise clock, a receiver can obtain good 3-D location accuracy with only three satellites in a favorable geometry.

[2]The 10–12-meter SEP is based on the location accuracy *actually provided by GPS in practice,* even though this is better than the original GPS specification of 16 meter SEP (ARINC, 1991). SEP stands for spheroidal error probable. The error is spheroidal rather than spherical since the Z component is greater than the X or Y components. In this case, the 10 meters SEP means that there is a 50 percent chance that the object is located within a sphere 10 meters in radius. To approximately translate from SEP to CEP (circular error probable), multiply SEP by 0.75. The three-dimensional location accuracy of SEP is required in some military applications, such as in the operation of GPS-equipped cruise missiles. In other cases, the two-dimensional location accuracy of CEP is adequate, such as in artillery fires. Only three GPS satellites are required to obtain two-dimensional coverage for CEP calculations.

the full GPS satellite constellation, most places on the Earth's surface have line-of-sight to four, five, or even six satellites at any given time.[3]

The U.S. military and other authorized users (e.g., NATO allies) retain private access to the most accurate GPS transmissions (PPS) by receiving a more precise GPS transmission called a P-code. Civilian access (C/A) to GPS transmissions are less accurate than military access by roughly a factor of two (when S/A is off). Therefore, given widely available GPS receiver equipment, U.S. military location accuracy is to within 10–16 meters SEP, while civilian and other nations' military location accuracy is to within 20–30 meters SEP.[4] In addition, the U.S. Department of Defense can degrade the civilian access signal to a 54–76 meter SEP accuracy or more by turning on S/A.[5] Selective availability places additional error in the satellite's navigation message, which results in degraded location accuracy.

The representation of absolute GPS coverage in TLC/NLC will be relatively simple. A given set of four GPS satellites accessed by a specified ground receiver will have an area of overlap on the ground of about 1000 km on a side. An area of that size will generally cover the whole TLC/NLC theater of operations.[6] Therefore, the representation of absolute GPS coverage over the TLC/NLC theater of operations will be represented by a global variable called "GPS state."[7] The GPS state represents the number of GPS satellites expected to be over the theater in a favorable geometry at a given moment.[8] For example, a GPS state of

[3]The GPS system now has 24 Block II and Block IIa satellites in orbit, completing the 24-satellite constellation. The Air Force Space Command concept of operations states that GPS availability will be based on a 98 percent probability of maintaining 21 operational satellites. In addition, one must also consider the former Soviet version of GPS called GLONASS (Global Navigation Satellite System), which has about 12 of their 15 operational satellites in orbit. Since GLONASS uses frequency division multiplexing, it requires a different type of receiver than GPS, which uses code division multiplexing. However, integrated receivers are under construction that can access both GPS and GLONASS signals at the same time. In addition, GLONASS does not have or use S/A, so that users of GLONASS can benefit from increased location accuracy. Therefore, any analysis of potential enemy use of navigation satellites for combat must consider the use of GLONASS as well as GPS satellites. TLC/NLC does not intend to include GLONASS at this time, although it could be added using a methodology similar to the one described here.

[4]According to Sweeny (1993) the required accuracy for C/A code with S/A off is 30 meter SEP. In practice, accuracies closer to 20 meter SEP are often obtained by civilian users.

[5]According to ARINC (1991) and Sweeny (1993), the required accuracy for C/A code with S/A on is 100 meter 2 drms, or 76 meter SEP. Since the base location accuracy for C/A code is better in practice than the stated requirements, we estimate that the accuracy of C/A code with selective availability on will be closer to 54 meter SEP than the requirement of 76 meter SEP.

[6]The "footprint" of the GPS satellite coverage on the ground is ellipsoidal rather than square, as shown in Figure 3. However, since the TLC/NLC model usually defines a square boundary around the theater of operations, the GPS footprint is considered to cover the whole theater of operations.

[7]In this report, GPS state refers to the observability state, which is the number of satellites that can be observed by the receiver at a given time. This is not to be confused with the acquisition or tracking state of GPS receivers.

[8]Since the GPS satellites are in semi-synchronous orbits at a 55 degree inclination, it is sometimes difficult to obtain a sufficiently favorable geometry at certain locations on the Earth. Furthermore, there are a few "gaps" in GPS state four coverage that shrink or grow a bit as the

four means that from the ground, a GPS receiver will have access to four GPS satellites in a favorable geometry with which to perform accurate location calculations. A GPS state of three may mean that either only three satellites have line-of-sight to the receiver or that the geometry of four satellites is poor and therefore can provide only as much accuracy as three satellites with a good geometry. Since the location and orbits of the GPS satellites are well known, any gaps in coverage may be predetermined through off-line analysis. Neither the individual satellites nor their orbits require explicit representation in the TLC/NLC model.[9]

If the GPS state is greater than or equal to four, then the location accuracy provided to GPS receivers is normal (subject to P-code access and S/A). If for any reason (such as for analysis or lack of funding to maintain a full constellation of satellites) the GPS state drops below four, then the location accuracy available to GPS receivers may be further degraded. The degraded SEP is related to the base SEP by a multiplier. In Table 1, we estimated the effects of reduced effective satellite coverage on the SEP for a platform with and without an inertial navigation system (INS).[10]

If the GPS state is likely to change during the course of a model run, then the GPS state that applies across the theater at any given time can be stored as a sequence of numbers, only one of which applies at a given time. If the GPS state is going to be three for less than 15 minutes, there is no substantial effect on the location accuracy of INS- and GPS-equipped assets.[11]

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satellites move around the Earth. For a particular GPS state, we assume that the specified number of satellites are in a favorable geometry.

[9]To determine GPS state over time as inputs to the TLC/NLC model, some off-line calculations need to be run. The number of GPS state input values for TLC/NLC's level of resolution is about 432 values based on the following calculations: GPS satellites are sun-synchronous, returning to the same location every 12 hours. A 15-minute increment over 12 hours equals 48 time periods. If we divide the 1000 km on a side theater into approximately nine 330 km subregions, the result is 432 input values for GPS state. If a study requires a finer geographical distinction, a larger number of input values would need to be calculated.

[10]For munition targeting purposes, the INS could compensate for a GPS state of three for only a few minutes. Within an hour, the INS location accuracy has drifted by about one mile (depending upon the quality of the INS), which makes it useless for munition targeting. (Aircraft can navigate with INS since their INS receives additional location updates that reduce the effects of INS drift.) Without INS, the munition location error increases more quickly over even small time increments. Since the resolution of the GPS state over time is not intended to be tracked in TLC/NLC in time increments of less than 15 minutes, the presence of INS does not matter in the model if the GPS state is reduced to fewer than three for less than 15 minutes.

[11]For example, if the GPS state is initially four (assuming good geometry) and suddenly becomes three, there is no immediate effect. Aircraft or other assets with inertial navigation systems can continue to operate for a few minutes with no substantial location accuracy degradation. After an hour, the INS drift is about a quarter mile to a mile, depending on the quality of the INS. For targeting, the INS can keep the aircraft relatively on course for 15 minutes, as long as the GPS state returns to four for adequate terminal targeting accuracy.

Table 1

Approximate SEP Multiplier as a Function of GPS State

GPS State	SEP Multiplier with INS	SEP Multiplier without INS
Favorable (≥ 4)	1.0	1.0
Reduced (= 3)[a]	1.0	2.0[b]
Poor (< 3)	No GPS effect	No GPS effect

[a]For 3-D targeting, GPS state three can be used instead of GPS state four if the lack of the fourth satellite is for a short period of time (a few minutes). For accurate 2-D targeting (CEP), a GPS state of three is sufficient. This assumes emphasis on X, Y, and time coordinates, rather than on X, Y, and Z coordinates.

[b]Approximate value; precise value requires more detailed analysis.

In addition to GPS state, one should also define a selective availability variable with possible values of "on" and "off." When selective availability is on, the absolute GPS location accuracy provided to C/A-code users is about 54–76 meter SEP.[12]

As a reminder, U.S military P-code location accuracy available from GPS transmissions is higher than for other nations' military or civilian access. However, all users, including U.S. military and other nations' military and civilians, can improve their location accuracy using differential and relative GPS, as described below.

Representing Differential GPS Coverage

We will describe two types of GPS coverage in this subsection: coordinate correction and pseudo-range correction. Both types provide location error-correction data to GPS receivers, although the method of correction differs for each type.

Coordinate Correction Differential GPS

The most common and least expensive form of coordinate correction differential GPS is provided by an additional GPS transmitter stationed at a known location, usually on the Earth's surface.[13] This additional transmitter site collects GPS

[12]Note that the elective availability degradation of the GPS signal can be highly variable to keep any likely opponent guessing. However, the large number of civilian and allied users of GPS may preclude extreme variations in S/A in future conflicts. For purposes of analysis using the TLC/NLC model, selective availability will be either on or off.

[13]Placing a differential GPS transmitter at a known location on the Earth is the most common and easiest method of fixed reference for differential GPS. However, even a moving object with an

satellite transmissions over time, compares the location observations in these transmissions to its own known location, and sends the coordinate correction data to GPS receivers that are within transmission or relay range. As long as the location of this additional transmitter is known to a high degree of accuracy, the P-code accuracy of the user receivers is improved to about 2–4 meter SEP. The differential GPS location accuracy for C/A code is 4–8 meter SEP.[14]

Note that the civilian access code using coordinate correction differential GPS can in fact exceed the location accuracy of absolute military P-code access. One reason is that the use of differential GPS mostly eliminates both the selective availability error and the systematic space and control bias errors. As a result, civilian access differential GPS can provide better location accuracy than can ordinary absolute military access (4–8 meter vs. 10–16 meter, respectively). However, this advantage is a function of the distance to the differential GPS transmitter.[15] The farther away from the transmitter, the less accurate is the location accuracy of the receiver. As a rule of thumb, SEP increases one meter for every 50 miles (about 80 km) of range up to about 320 km. Therefore, somewhere between 300 and 350 km, the coordinate correction differential GPS transmitter and the receiving platform will not share the same four satellites and thereby violate the applicability of coordinate correction differential GPS use.

Any location errors in the placement of the "known" site are passed along to the receivers. However, a fixed site can average the signals it receives from GPS transmissions over time and thereby increase the location accuracy by reducing the effect of random GPS error. This dependence on good known location accuracy is what makes it difficult to provide good differential GPS data from moving platforms.

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accurate inertial navigation system could be used as a differential GPS transmitter as long as the INS drift remains small. In addition, GPS receivers that automatically perform time averaging tend to be more accurate than GPS receivers that simply take location "snapshots."

[14]In DOT/DOD (1992), p. A-41, the stated radio-navigation capability of C/A code differential GPS access is better than 10 meters 2 drms, which is equivalent to 6 meter SEP. Differential GPS P-code accuracy can get down to 1 meter SEP under favorable geometry and environmental conditions. Similarly, differential C/A code can also benefit from these favorable conditions, and may achieve 3 meter SEP location accuracy.

[15]The differential GPS location accuracy is also a function of the time between bias correction updates. These updates should be frequent enough to counter the effects of selective availability. As a result, differential GPS will require virtually continuous updates in the face of rapidly changing S/A. It should be noted that regardless of whether S/A is on or off, or whether P-code or C/A code is being used, the location coordinates provided by a GPS receiver will tend to "wander" over time. That is, a stationary receiver will provide GPS coordinates that appear to change over time. This wander effect is larger for C/A code when S/A is on, and is of a different and larger magnitude than the apparent wander for P-code receivers. Differential GPS also minimizes this wander effect.

Pseudo-Range Correction or Wide-Area Differential GPS

As mentioned above, *coordinate correction* differential GPS determines its observed location from GPS signals, compares the observed location to its known location, and then sends the coordinate corrections to any receivers in its vicinity. The reason this method is limited to sharing the same four satellites is that the difference between the observed and the actual location makes sense only with respect to that observation, which is based on four specific satellites.

Pseudo-range correction differential GPS avoids this limitation by calculating and transmitting correction factors for *each satellite in the constellation*. Although the correction factors may be updated only each time the satellite is observed, the correction data for each satellite are stored and transmitted for all satellites in the constellation.[16] As a result, there is no range limit per se on pseudo-range correction differential GPS (also called wide-area GPS). There is a degradation in location accuracy that increases roughly linearly with distance as described above, but the coverage of wide-area GPS may be global.[17]

Differential GPS Representation in TLC/NLC

The representation of both types of differential GPS coverage in TLC/NLC is relatively straightforward. Wide-area GPS is easily represented as improved location accuracy across the theater of operations, although the location accuracy may be slightly worse because of range considerations. The assumed scenario will determine the type of differential GPS coverage available and the effects of range restrictions, if any. The rest of this subsection describes the design features necessary to implement coordinate correction differential GPS in TLC/NLC.

For coordinate correction differential GPS coverage, both the location of the transmitter and the area covered by its line-of-sight need to be placed on the TLC/NLC map. An off-line calculation should be made to determine the outline of the area of effective transmission, and this area should be included as a region in TLC/NLC. The TLC/NLC preprocessor will determine which nodes on the

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[16] Absolute GPS is also called a "point" solution method, since location accuracy is determined from a single point. Coordinate correction differential GPS is also called "relative" GPS, since the receiver location accuracy is calculated relative to a known point. Pseudo-range correction is also called a "network" solution, since correction data are stored for the whole network. (Pseudo-range is a GPS-specific technical term associated with the apparent location of each satellite.) We avoided using these terms to preclude confusion between relative solution GPS and relative targeting GPS, described in the next subsection.

[17] INMARSAT is offering to transmit wide-area GPS signals across the globe from the communications satellites in geosynchronous orbit. In addition, the Advanced Research Projects Agency (ARPA) is working on a local wide-area GPS transmission system called Common Grid, which is designed to give 3–4 meter SEP accuracy in a theater of operations.

various TLC/NLC networks could receive differential GPS transmissions. Since differential GPS transmitters tend to be useful from only known locations, they are not likely to change frequently during a TLC/NLC run.

One region should be provided for each transmitter, and the effects of the region should be a function of whether or not the transmitter is still operating. Of course, coordinate correction differential GPS transmissions are useful only if both the correction transmitter and the receiver can receive absolute GPS transmissions as well.

Coordinate correction differential GPS location correction transmissions can also be relayed to various receivers. If these relay stations are used in the model, then the line-of-sight area of the relay stations could also be represented in TLC/NLC.[18] Since this may significantly increase the number of differential GPS relay sites in TLC/NLC, one may instead base differential GPS transmission relays as a function of the normal communications capabilities represented in the model. In either case, the location accuracy of the differential GPS is still based on the receiver's distance from the fixed transmitter and not based on the location of the relay stations.[19] The maximum distance for effective coordinate correction differential GPS transmissions is between 300 and 350 km, since that is the maximum distance between receivers sharing the same four GPS satellites. See Figure 3 for examples of absolute, differential, relative GPS targeting and offset targeting.

Representing Relative GPS Targeting

Relative GPS targeting is a method by which munitions can be more accurately guided to their targets.[20] Since relative GPS targeting is easily confused with offset targeting, the next subsection will describe offset targeting and how it differs from relative GPS targeting.

Relative GPS targeting does not attempt to determine a precise target location through absolute GPS methods. Instead, the location of the target is measured

[18]Communications are not yet explicitly represented in TLC/NLC. To represent the relay of GPS transmissions, the GPS receiver simply has to be within the region of coverage (including relay) described above.

[19]In all cases, bias corrections tend to be transmitted every 5 to 10 minutes unless the S/A is changing more quickly. Currently, S/A changes every few hours, although it can be changed more frequently in wartime. If this becomes a study issue, an additional parameter will be required for the frequency of S/A changes. However, because of the time resolution in TLC/NLC, it is unlikely that such changes would be represented explicitly. Neither the changes in S/A nor the relayed differential GPS updates are sufficiently large enough factors to appear in TLC/NLC.

[20]As noted above, the relative GPS targeting is different from relative GPS location determination, which is coordinate correction differential GPS.

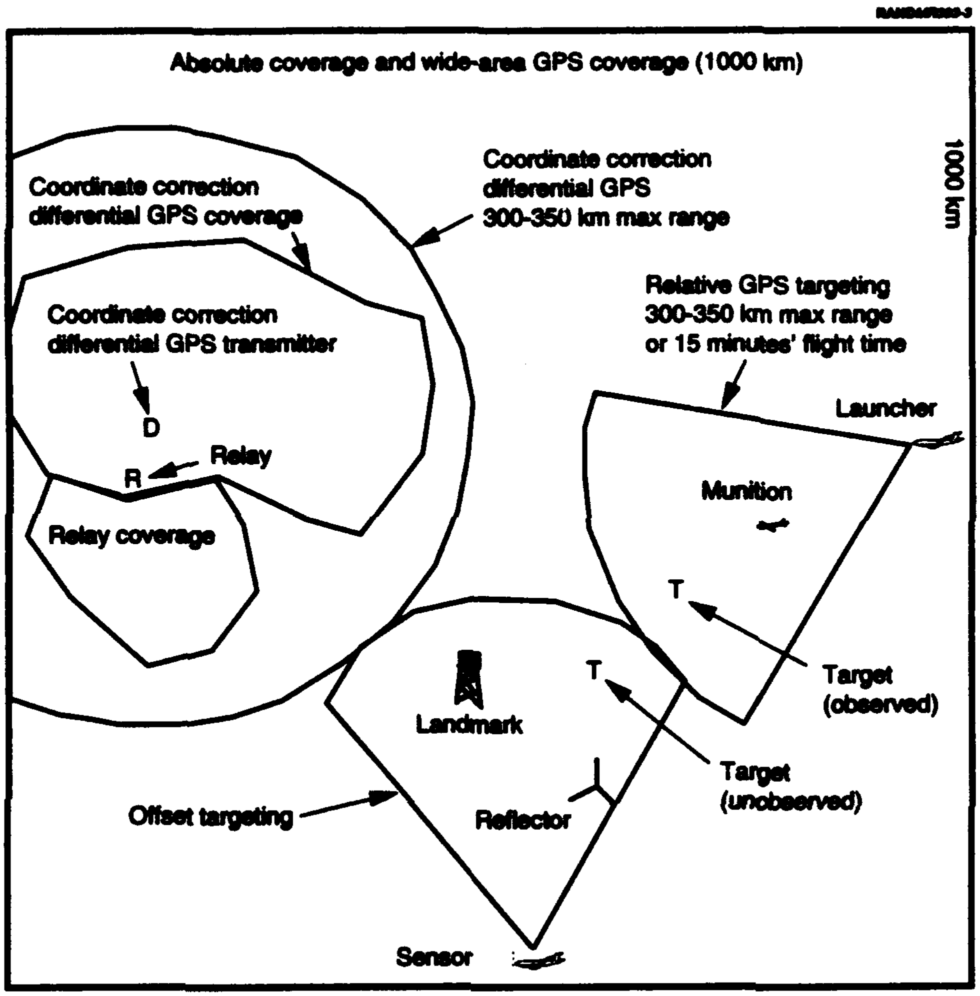

Figure 3—Examples of GPS Coverage and Offset Targeting

relative to a GPS-equipped platform, and that platform's apparent GPS location is known with respect to the target. For example, assume that an aircraft with a sensor (such as an imaging radar) has line-of-sight to the target. The aircraft does not know the exact location of the target (i.e., the GPS coordinates of the target are not known), but the aircraft does know its own location fairly accurately because it is GPS-equipped. Since the aircraft's sensor can provide good direction data to a munition launched from the aircraft, the GPS-equipped munition can be guided more accurately from the aircraft to the target than if launched without relative GPS.

A prerequisite for a GPS-equipped munition to be guided from a GPS-equipped aircraft to the target using relative GPS targeting is that both the aircraft and the

munition share the same four satellites. Just as coordinate correction differential GPS requires the same four satellites, so does relative GPS targeting. As a result, relative GPS targeting is limited to the minimum of about a 300–350 km range or a 10–15 minute (munition) flight time.

The process of relative GPS targeting allows errors common to both the sensor platform and the munition to be eliminated from the calculations. As a result, relative GPS targeting can achieve an approximate 5–8 meter SEP munition accuracy for a P-code GPS-equipped platform and munition combination, which is more accurate than absolute GPS targeting, but less accurate than coordinate correction differential GPS.[21]

The representation in TLC/NLC of relative GPS targeting is straightforward. Given a platform equipped with GPS and a precise direction and distance sensor, and given a GPS-equipped munition with a flight time of less than 15 minutes, then the accuracy of this platform/sensor combination is improved as a result of a munition accuracy of about 5 meters SEP (see Frost and Schweitzer, 1993). If the flight time is greater than 15 minutes, the target location error is increased. If the munition has an inertial navigation unit on board, the drift effect should be calculated as starting at the time that the shared geometry is lost. Because TLC/NLC determines the lethality against the target as a function of the type munition, type platform, and type target, the effective lethality can be determined off-line from the TLC/NLC model.[22]

Offset Targeting

In offset targeting, the location of the target is not known, but some sort of landmark is used to help guide munitions against the target. For example, the target may be an underground bunker not directly visible to the weapon platform. However, from other information sources, such as HUMINT (human intelligence), the location of the bunker is known relative to some landmark or other readily identifiable feature, such as a tower. The landmark may be used to help guide the munition from the platform to the target.

[21]There are many assumptions required to achieve 5 meter SEP munition accuracy, including a P-code GPS receiver and inertial navigation system on both the platform and the munition, and an accurate sensor on the platform, such as synthetic aperture radar. See Frost and Schweitzer (1993) for a detailed description of relative GPS targeting.

[22]Other factors may be included as modifiers of these three basic factors, such as terrain, weather, and the presence of intelligence assets like the Joint Surveillance and Target Acquisition Radar System (J-STARS) to support targeting.

Since the location of the target is not well known, the accuracy with which the munition is guided to the target is a function of location accuracy of the landmark and the location of the target relative to the landmark. For example, assume the target is an underground bunker and the landmark is a tower some 3 km northwest of the target. If the only information available is that the landmark's location accuracy is within 25 m SEP, the range to the target is 100 m SEP, and the direction to the target is known within 3 degrees azimuth, the resulting target location accuracy is not very good.

However, if a reference receiver could be placed at the tower, perhaps by a GPS-equipped special forces team, then the location accuracy of the landmark tower has been improved by a factor of five. Moreover, the team might also be able to provide triangulation data to the target by taking another location reading nearby. Using a range finder and triangulation, the location accuracy of the target may be significantly improved, even without the team physically visiting the target site.[23]

If the platform is also GPS-equipped, then the location accuracy of the platform can also be improved. This is true for land platforms as well as for sea and air platforms. For example, artillery and surface-to-surface missile launchers need to pinpoint their own location in order to provide accurate fires. GPS can help reduce self-location errors, thereby improving the overall munition accuracy.

Note that offset targeting is a different method from relative GPS targeting. In relative GPS targeting, the GPS-equipped platform relies on common location data, accurate direction, and accurate range information to guide the GPS-equipped munition to an observed target. In offset targeting, the target is unobserved, its location is known relative to a landmark, and the location accuracy of both the landmark and platform may be known to varying degrees, which may be improved by GPS receivers at the landmark or the platform or both. Range and direction information from the platform to the landmark, and from the landmark to the target, must also be considered.

[23]There are many ways to place GPS receivers behind enemy lines to enhance offset targeting. See Section 4 on increased target location accuracy.

3. GPS-Equipped Assets and Prerequisites for GPS Benefits

Only GPS-equipped assets can directly benefit from GPS transmissions.[1] Absolute GPS transmissions are required for all three GPS methods—absolute, differential, and relative. If an asset is equipped to handle absolute GPS, then the nationality of the side matters. U.S. military assets (or similarly equipped allied assets) will have better location accuracy because of their access to the P-code. If selective availability is on, non–P-code users would have their location accuracy further degraded. Both U.S. and non-U.S. military assets could improve their location accuracy by receiving transmissions from differential GPS transmitters. Platform and sensor combinations equipped to benefit from relative GPS targeting need to be identified for purposes of assessment. Finally, GPS-equipped assets require line-of-site to the satellites, but the line-of-sight may be blocked by foliage in forest and jungle environments.

The first subsection below describes the representation of GPS-equipped assets, while the second subsection describes the prerequisite conditions that must be met before GPS-equipped assets can benefit from GPS transmissions. The third subsection describes how foliage may preclude line-of-sight to the satellites, and how this affect will be broadly represented in TLC/NLC.

GPS-Equipped Assets

Platforms and certain munitions within TLC/NLC will require a new attribute called "GPS access." To efficiently represent the various types of GPS access in TLC/NLC within a single attribute, the following values will be associated with the attribute listed:[2]

- None
- C/A code, no differential access

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[1]Assets not equipped with GPS can also benefit from being in proximity with GPS-equipped assets. Since TLC/NLC only operates flights of aircraft or ground maneuver battalions, the issue of equipping only selected assets with GPS becomes moot. As long as key elements are considered GPS-equipped in TLC/NLC, the flight or unit is considered to benefit from GPS.

[2]It may be easier to divide this single attribute into two separate attributes: code access and solution method. For purposes of analysis, the analyst may choose to reduce the number of combinations available for use in a single study.

- P-code, no differential access
- C/A code, coordinate correction differential access
- P-code, coordinate correction differential access
- C/A code, wide-area access
- P-code, wide-area access.

Note that even if a C/A code coordinate correction differential access value is attributed to a given platform, the platform will have increased accuracy only if it is within range of a differential GPS transmitter or relay station. In addition, the location accuracy of a coordinate correction differential (CC diff) system is dependent on the distance from the fixed transmitter to the receiver and limited by a maximum distance.

A second attribute, called "relative GPS targeting capability," will be required on appropriate sensor-type platforms. If the platform, sensor, and munition combination is appropriate to apply relative GPS targeting, then the munition accuracy will be increased (up to a 300–350 km maximum range or 15 minute munition flight time). Only the values of "yes" or "no" are required for this attribute.

Prerequisites for GPS Benefits

GPS transmissions can benefit military or civilian GPS-equipped assets only under a specific set of conditions. If these conditions are not met, the benefits cannot be accrued. We will define the prerequisites in a sequence of questions readily translated into computer code. This sequence is shown in Figure 4.

The first question is whether the platform or munition is GPS-equipped. If not GPS-equipped, then the platform does not receive any GPS benefit. If the asset is GPS-equipped, then the type of access must be determined (i.e., P-code vs. C/A code, absolute vs. differential vs. relative).

The second question is whether selective availability is on. If so, then any non-U.S. military absolute GPS access is further degraded. Next, the base value for location accuracy may be determined from Table 2,[3] which assumes a GPS state

[3]Note that if the model's resolution of lethality or probability of kill is in much broader bands so that the difference between 4 and 10 meters does not matter, one can significantly reduce the degree of resolution in the GPS submodel. As long as the aggregate effects are represented, the detailed effects need not be represented to a level of detail beyond the resolution of the TLC/NLC model.

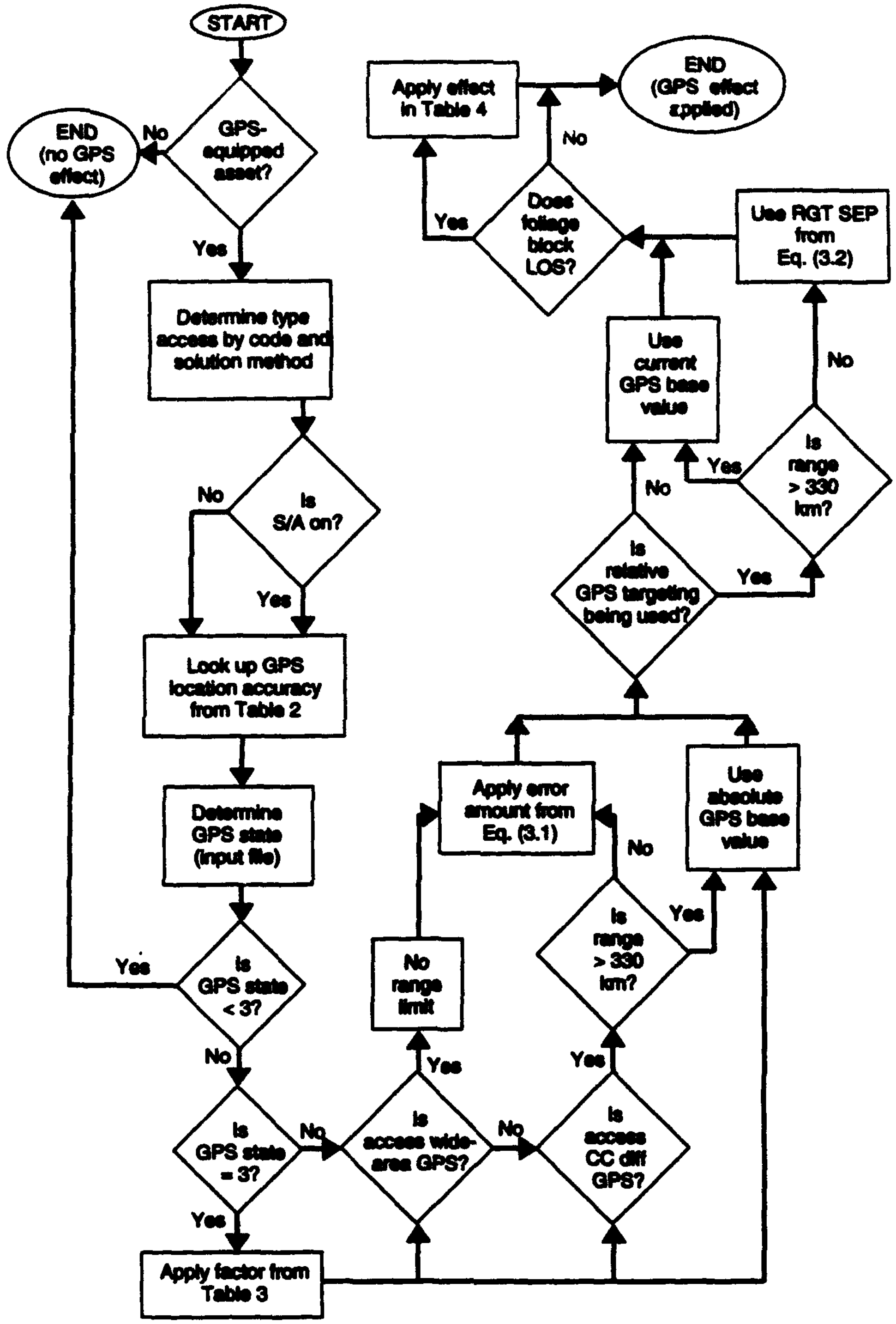

Figure 4—Flowchart of GPS Prerequisite Model Logic

Table 2

Estimated SEP (meters) Based on Access, S/A, and Solution Method

GPS State	Selective Availability (S/A)	Absolute GPS P-code	Absolute GPS C/A code	Differential GPS P-code[b]	Differential GPS C/A code
≥ 4	Off[a]	10–16	20–30	2–4	4–8
≥ 4	On	10–16	54–76	2–4	4–8

[a]If accessing GLONASS signals, use S/A off (there is no S/A for GLONASS).

[b]Differential GPS accuracies for P-code can reach 1 meter SEP given good geometry and environmental conditions.

of greater than or equal to four. The accuracy for relative GPS targeting will be applied after the base location accuracy value has been determined.

The third question to ask is "What is the GPS state?" If the GPS state is greater than or equal to four, then GPS-equipped assets may receive full benefit from absolute GPS transmissions. If not, then all of the derived GPS benefits (wide-area differential, coordinate correction differential, or relative GPS targeting) are reduced during this assessment cycle, as described in Table 3. Note that the GPS state is the basis of all subsequent calculations. The location accuracy provided by absolute, differential, and relative GPS are all calculated on the base location accuracy provided by the GPS state.

The fourth question is whether wide-area differential GPS is being used. If so, then there is no maximum range limitation, although there is a range degradation effect. The increase in location accuracy is about 1 meter SEP for every 80 km, as shown in Eq. (3.1)[4]

Table 3

Approximate SEP Multiplier as a Function of GPS State

GPS State	SEP Multiplier with INS	SEP Multiplier without INS
Favorable (≥ 4)	1.0	1.0
Reduced (= 3)[a]	1.0	2.0[b]
Poor (< 3)	No GPS effect	No GPS effect

[a]For 3-D targeting, GPS state three can be used instead of GPS state four if the lack of the fourth satellite is for a short period of time (a few minutes). For accurate 2-D targeting (CEP), a GPS state of three is sufficient. This assumes emphasis on X, Y, and time coordinates, rather than on X, Y, and Z coordinates.

[b]Approximate value; precise value requires more detailed analysis.

[4]As shown in Beser and Parkinson (1984), the maximum error can be determined based on the apparent difference in the location and the actual location of the GPS satellite. In practice, however, the maximum error is not obtained, and the effects can be mitigated by knowledge of the true satellite location. Therefore, we have estimated an average error amount to add to the differential GPS location accuracy for purposes of analysis in the TLC/NLC model.

$$\text{Add to SEP: } 1 \text{ m} * (\text{range to transmitter}/80 \text{ km}) \quad (3.1)$$

The fifth question is whether coordinate correction differential GPS is being used. If so, there is a maximum range limitation of about 300–350 km, for reasons described in the last section. Even within the maximum range limit, there will be a location accuracy range degradation, as shown in Eq. (3.1).

The sixth question determines whether the platform, sensor, and munition combination is adequate to perform relative GPS targeting. If the target is beyond the 300–350 km maximum range limitation or the munition has greater than 15 minutes flight time, then relative GPS targeting cannot be used. The currently available GPS location accuracy (as calculated so far in the flowchart) must be used instead. If the target is less than 300 km from the platform, the current location error base value is multiplied by the relative GPS targeting factor, as shown in Eq. (3.2).

$$\text{RGT SEP} = 0.5 * \text{current GPS base value} \quad (3.2)$$

where RGT stands for relative GPS targeting, and the current GPS base value is either absolute or differential GPS, P-code or C/A code access, with or without selective availability on, as a function of GPS state, as shown in Tables 2 and 3.

The seventh and final question is whether foliage blocks line-of-sight from the receiver to the satellites, as described in the next subsection.

Effects of Foliage on GPS Receivers

The GPS signal attenuates rapidly in foliage. As a result, if dense foliage blocks the line-of-sight between the GPS receiver and the satellites, the receiver will not be able to obtain or retain lock on the GPS signal.

In most cases, air and naval units will not need to worry about foliage blocking line-of-sight during operation. Only ground units will need be concerned about losing the GPS signal in foliage. Moreover, only mobile ground assets will be affected, since stationary ground assets can often find a clearing or climb a tree to obtain and retain the signal lock. (It may not be an elegant solution, but it's cheap and it works.)

Ground assets on the move will not be able to maintain continuous self-location accuracy through GPS in forested areas, especially in tropical areas. Moreover, the ability to obtain lock on the GPS signal will be difficult unless the assets stop and find a location (perhaps a treetop) with a clear line-of-sight to the satellites.

It would not be appropriate to represent this effect as an increase in the SEP or decrease in location accuracy, since the accuracy is still good, just not always available. Instead, we recommend directly modifying the benefit accrued to GPS-equipped ground assets, as described in Section 4. For example, if GPS allowed the speed of a ground unit to be increased 15 percent in clear terrain, the unit speed would be increased only 10 percent in forested areas and 5 percent in tropical jungles, as shown in Table 4.

In addition, the inability to maintain a continuous GPS signal lock is important when facing a GPS jamming threat, as discussed in Section 5.

Table 4

Effect of Foliage on Ground Asset Benefits

Type of Terrain	Multiplier of Increase in Unit Speed[a]	Multiplier of Reduction in Congestion Rate[b]
Clear	1.0	1.0
Forested	0.67	0.67
Jungle	0.33	0.33

[a]This is not a multiplier of the unit's overall speed, but a multiplier of the increase in unit speed that would be allowed by continuous or instantaneous GPS access.

[b]This is not a multiplier of the unit's rate of congestion while moving, but a multiplier of the reduction in the rate of congestion for the unit as a result of continuous or instantaneous GPS access.

4. Effects of GPS Transmissions on GPS-Equipped Assets

Given a representation of absolute, differential, and relative GPS coverage in TLC/NLC, and given a representation of which types of assets can benefit from each type of coverage, we need to define exactly the types of benefits that accrue from improved location accuracy and describe how these benefits are represented in the model. The subsections below present the three specific areas of benefits: improved self-location accuracy, increased target location accuracy, and the benefit of stand-off munitions launch.[1]

Note that each of these benefits is independent of darkness and most weather effects.[2] In addition, GPS receivers are passive (nontransmitting), which improves asset survivability when compared to active (e.g., radar) position-navigation devices. If one is comparing different types of position-navigation devices, the passive aspect of GPS should be part of the analysis.

Benefit of Improved Self-Location Accuracy

GPS can provide improved location accuracy of an asset equipped with a GPS receiver. This is true whether it is absolute GPS or differential GPS. (Relative GPS targeting applies only to improved munition accuracy, not platform self-location accuracy.) Improved self-location has two main benefits: improved navigation and reduced fratricide through reduced location error.

Improved Navigation to the Destination

The use of GPS for improved navigation means that those operating GPS-equipped assets are less likely to get lost and more likely to reach the desired

[1]Another GPS benefit is time synchronization, which allows for better tactical coordination, improved methods of encryption, and improved communications through time phasing and beam pointing. Most of these benefits are below the level of resolution of the TLC/NLC model and are not included in this design. If an analyst can define the aggregate effects that describe these benefits, they could be included in the model at a later date.

[2]The only environmental effects that affect GPS signals are ionospheric and tropospheric disturbances, neither of which is represented in TLC/NLC. The effects of such disturbances on the GPS state should be calculated off-line.

destination. This benefit can be represented in a number of ways in TLC/NLC, depending on the type of asset and the resolution within the model.

For example, a flight of GPS-equipped aircraft may attempt to fly to the primary target. In the high-level design of the TLC/NLC air combat model engagement and attrition processes, there is a probability P_1 that the aircraft will reach their primary target (see Allen, 1993).[3] This probability is increased if the aircraft use navigational aids such as GPS. A similar calculation is used for the probability of reaching the secondary target.

Another example deals with GPS-equipped ground units. At the moment, few combat models include any representation of ground forces getting lost, although such a representation may be created in the future. For example, the area over which the allies undertook the "left hook" during Operation Desert Storm was an Iraqi training area where Iraqi forces usually got lost. We propose the following four representations of benefits for aggregate ground units using GPS, listed in order of the simplest to the most complicated:

- Increase the average movement rate for each (battalion-sized) ground unit in TLC/NLC.
- Decrease the average unit length. (This controls congestion in TLC/NLC, which affects the maneuver speed of larger formations, such as brigades, division, and corps.)
- Enhance the ground maneuver network in TLC/NLC for the GPS-equipped side. (This represents the advantage of GPS in providing the ability to navigate in areas denied to a non–GPS-equipped opponent.)
- Other representations of getting lost could include units randomly "taking the wrong turn" in the movement network, or at least waiting longer at the crossroads before continuing its movement.

Whichever form of penalty is used to represent reduced land navigation benefits, the representation should be both simple and credible.[4] At this time, we plan to implement the first two, and possibly the third, representations of the benefits of GPS on ground maneuver in the TLC/NLC model.

[3]In TLC/NLC, the probability of not reaching the target due to navigation error is separate from the calculation of not reaching the target due to attrition.

[4]It has been suggested that GPS also can be used to improve the ability of a unit to traverse a minefield. However, the GPS location error tends to change over time, and 50 percent SEP means that the receiver has only a 50 percent chance of being within 10 meters of its reported location. As a result, unless the minefield is very sparse, GPS location accuracy will not be of major assistance in traversing land mines. Naval mines, in particular, are difficult to detect and tend to move with the current. As a result, GPS would not be very useful in traversing around free-floating mines. Traversing fixed naval minefields entails the same risk as using GPS to traverse land minefields.

We also plan to improve the accuracy of artillery and surface-to-surface missile fires. Artillery and surface-to-surface missiles benefit from improved self-location accuracy resulting from better knowledge of their own location. For example, if the location of the firing battery is better known, its ability to place fires accurately on the target will be improved. In addition, if the forward observer has improved knowledge of his own location, he can direct more accurate fires on the target.

Another example is the benefit of GPS for self-location accuracy provided to special operations forces (SOF). SOF teams using GPS can improve their navigation on insertion, resupply, targeting, ground movement, and extraction. In each of these cases, lack of location accuracy can lead to unnecessary losses and mission aborts.

Search and rescue is another mission that can benefit from GPS self-location accuracy. The location accuracy of both the downed pilot and the rescue team are improved, thereby increasing the chance of mission success.[5]

Reduced Fratricide

Historically, indirect fire has been a principal source of fratricide. Yet during Desert Storm, there were no reported cases of U.S. indirect fire fratricide, even though friendly forces attempted to call indirect fire on other friendly forces on a number of occasions. The main reason these calls for fire were canceled at the fire-direction center was that the maneuver units frequently were able to accurately report their positions because of GPS.[6]

Based on experiences such as these, the representation of fratricide in TLC/NLC is an important aspect of determining the effects of space assets on the battlefield. Fratricide tends to occur when there is uncertainty as to the identity or location of friendly forces. In many cases, identity may be assumed based on location.[7]

[5]The current plan is to not include the benefits of GPS provided to SOF and search and rescue operations directly in the TLC/NLC model, but to address such issues off-line. The outputs of the TLC/NLC model can, however, be used as input data for the analysis. For example, the number of friendly aircraft downed over enemy territory as represented in the model provides the demand for search and rescue operations over time. The enemy air defense and ground forces in the area provide the threat to the rescue team.

[6]From the transcript of a taped interview with the combatants at the battle of 73 Easting, Operation Desert Storm.

[7]In addition to good self-location accuracy, a good command, control, and communications system and set of procedures are required to preclude fratricide. Without the ability to communicate and monitor friendly positions and control fires, improved self-location accuracy alone will not reduce fratricide. However, improved self-location accuracy does reduce fratricide if the other prerequisites are already in place.

To include fratricide in TLC/NLC, we need to represent a degree of uncertainty as a function of the situation. The more uncertainty, the greater the likelihood of fratricide. The less uncertainty, the lower the likelihood of fratricide. Accurate and frequent position location reporting will reduce the degree of uncertainty of friendly force location, and thereby reduce fratricide. A presentation is available from the author on a need-to-know basis regarding air-to-air and ground-to-air fratricide as a function of the situation. For ground-to-ground attrition, modifiers to the availability factors in the CADEM (Calibrated Differential Equation Methodology) attrition process should be considered.[8] (CADEM is a continuous differential version of the ATCAL (Attrition Calibration) killer-victim scoreboard methodology for representing ground-to-ground attrition in aggregated combat models; see Moore, 1993.)

Benefit of Increased Target Location Accuracy

There are three primary benefits to increased target location accuracy: increased lethality against fixed and mobile targets, faster production of increased accuracy of target location, and the ability for additional platforms to provide target designation.

Increased Lethality Against Fixed and Mobile Targets

Fixed targets may be located by various means to a fairly good degree of accuracy. If GPS receivers can be placed on semi-autonomous munitions, they can find their way to the target. If equipped with both GPS receiver and an inertial navigation system, these munitions can have very good accuracy, subject to enemy countermeasures (see Section 5). These smart munitions may be guided by absolute or differential GPS. A platform with a precise direction and distance sensor with line-of-sight to the target and a GPS-equipped munition can also obtain increased lethality through the use of relative GPS targeting, as described earlier.

Lethality against mobile targets may be improved through a second use of relative GPS. Mobile targets that appear within the same field of view as features whose locations are well known are susceptible to more accurate targeting. The

[8]Simply using a fraction of friendly forces killed by fratricide or a killer-victim scoreboard in which friendly forces may engage other friendly forces is not an adequate representation of fratricide. Assessing friendly casualties resulting from fratricide at a certain fixed rate independent of the degree of uncertainty does not represent the cause of fratricide or ways to reduce it. Once uncertainty is included, fratricide and be adequately addressed, and the effects of improved location accuracy and reporting can be measured.

absence of any known features in the same field of view makes it more difficult to attack mobile targets. Mobile targets may be attacked by munitions that are either GPS-equipped or non–GPS-equipped, depending on the degree of target location accuracy obtained and the time from detection to attack.

An added benefit to increased target location accuracy is a possible reduction in munitions expenditure. The more accurately the location of the target is known, the fewer munitions of a given type need to be allocated as a hedge against target location uncertainty.[9] This reduced munition expenditure benefit applies both to air-launched stand-off munitions and ground-launched indirect fire munitions, such as artillery and surface-to-surface missiles.

In TLC/NLC, this increased lethality will be a function of the type of munition and type of platform. In addition to the attributes added to TLC/NLC platform and munition objects, data on how increased accuracy relates to increased lethality must be provided to the TLC/NLC modelers.

Faster Production of Increased Location Accuracy of Target

The time it takes to process a target's location can be extensive, depending on the circumstances. For example, a mobile sensor detects a target, but the rapidly changing location of the sensor and its changing orientation to the ground and the target make it difficult to determine the target's actual location. There are software methods available to transform or warp the picture obtained by the sensor onto a standard planning map, but this can take a while. If the target is mobile, such as a SCUD launcher, the time required to transform the picture may exceed the time available to attack the target.

GPS could help reduce the time it takes to correlate the sensor picture to the map by referring the target's location relative to objects whose locations on the map are already known. This reduction in processing time may be sufficient to attack a mobile target within the window of opportunity. For example, small air-delivered GPS-equipped radar transponders could provide reference points behind enemy lines. Such reference points would allow for offset targeting as well as reduce the time required to process stand-off sensor data, such as from J-STARS or TR-1. If the transponder were moved, it would automatically update its new location using its GPS receiver. Such transponders may be destroyed, but

[9]In TLC/NLC, for example, the number of munitions that need to be delivered to the target (determined during mission planning) is a function of the effectiveness of the munition. The more effective the munition, the fewer rounds are required to achieve the desired level of damage to the target. Since fewer rounds are required to achieve the desired level of target damage, the overall munitions expenditure is reduced.

they first must be found. Both the radar transponder and the GPS receiver are difficult to detect and locate for destruction. Proliferation of these devices in the rear area complicates the challenge.[10]

Faster production time will increase the accuracy of attacks against mobile targets under these circumstances. TLC/NLC needs data on the time saved in processing and how that time translates into increased lethality against a mobile target given the type of platform, munition, and sensor.

Additional Platforms That Can Provide Target Designations

Many weapons platforms have target designators that can guide munitions to targets. Some of these designators place a beacon or reflect a beacon from the target so that the munition can be guided to the target. Others simply radio the information, as would an observer on the ground or in the air.

Relative GPS targeting and offset targeting allow more platforms to act as real-time or near real-time target designators than have been available in the past. For the two reasons given above, many sensors could be processed sufficiently quickly to allow weapons platforms to attack the target within a narrow window of time. Special forces teams could also use GPS for improved targeting. In some cases, the location of fixed installations "visited" by the team could be verified to a degree of accuracy not possible by other means. Such data could be obtained well before the weapons are launched to the target. Mobile targets that appear within the team's field of view could be targeted relative to known locations also in their field of view.

Many assets could contribute to improved targeting through GPS equipment. For example, special forces and other deep reconnaissance assets can provide GPS-based targeting data, depending on how long they have been in place and whether they have been able to operate in the area. This will probably not require additional attributes on TLC/NLC objects, but will require data on how accurately and quickly the information gathered by such means can be obtained and provided to the weapons platforms.

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[10]There are many types of reflectors that could be used in addition to radar transponders. Laser reflectors and other devices could be used to indicate relative location, while the GPS reference receiver could be used to determine absolute location.

Benefit of Stand-Off Munitions Launch

The benefits of stand-off munitions launch come in two categories: reduced vulnerability of the launching platform to enemy threats and the savings in time and fuel for the launch platforms. The second benefit also increases the number of targets that could be engaged by a stand-off platform during a single sortie.[11]

Reduced Vulnerability to Enemy Threats

GPS-equipped munitions allow for strikes to be conducted from much farther away than in the past because of the munition's (and the target's) increased location accuracy. Friendly air assets that are able to launch outside of the range of enemy air defenses (ground or air) are less likely to be engaged by the enemy assets, and therefore have increased survivability.[12] Similarly, ground-based platforms with stand-off munitions can fire with little chance of enemy retaliation if launched outside the range of enemy assets. In either case, the range of the stand-off munitions can reduce or sometimes negate the effects of enemy threats to the launching platform.

In TLC/NLC, assets equipped with stand-off munitions will be able to avoid some or all of the air defenses at a target, especially the *terminal defenses.* TLC/NLC needs data on lethality given the stand-off range of each type of munition, as well as the lethality of the air defense and other threats as a function of the stand-off range.

Reduced Flight Time to Engage Target Gives Fuel and Time Savings

Stand-off munitions also provide a benefit in terms of the reduced flight time required to deliver them (as compared to the time required to deliver close-in munitions). A platform attacking a single target will be able to cut many miles off its mission because of the munition's ability to travel a long way to strike a target. In addition, the ability to engage multiple targets using stand-off munitions during a single flight mission may reduce the total number of missions required to attack a target set.[13]

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[11]See also Section 5 on GPS countermeasures for threats against stand-off munitions launch.

[12]This assumes that likely enemy threat locations are known and that the opportunity exists to launch against targets while outside the threat envelope.

[13]Stand-off munitions also allow for off-axis deliveries, which can improve aircraft survival. However, this is below the level of resolution in the TLC/NLC model.

TLC/NLC needs data on the estimated fuel and time savings from stand-off munitions launch, as well as the number of targets that could be engaged by a single stand-off platform as opposed to a single platform that must penetrate to the target.

5. GPS Countermeasures and Counter-Countermeasures

We will discuss three areas of GPS countermeasures and counter-countermeasures: direct threats against the GPS transmitters, direct threats against the GPS receivers, and the threats against GPS signals. In all of these examples, either the United States or an enemy of the United States could use GPS countermeasures and counter-countermeasures.

Direct Threats Against GPS Transmitters

We discuss two types of direct threats against GPS transmitters: direct threats against absolute GPS satellites and direct threats against differential GPS transmitters.

Direct Threats Against Satellites

Since the GPS satellites operate in semi-synchronous orbits, most nations do not possess the capability to attack them directly. Most antisatellite (ASAT) platforms were designed to operate against low-Earth-orbit satellites, not satellites in higher orbits. Moreover, directed-energy attacks require substantial power and advanced technology, which few nations have. As a result, direct threats against GPS satellites are unlikely, unless the scenario calls for fighting against the Russians. Even then, there is some question as to how much of a threat against GPS satellites they could mount at this time or in the near future.

Counter-countermeasures to attacks on GPS satellites include maneuvering satellites, accessing GLONASS satellites, or launching additional satellites.

There is no plan to represent satellite objects or explicit orbits in TLC/NLC. That level of detail is not required for the studies currently planned for TLC/NLC. Due to the wide-area coverage of absolute GPS transmissions, the use of the global variable GPS state for the theater defined over time should be sufficient to address the results of ASAT operations analyzed off-line. As a result, the GPS

state parameter in the model, which may change over time, should be sufficient to represent the effects of direct threats to GPS satellites.[1]

One important caveat is that this report assumes a conventional (nonnuclear) threat environment. We have not included the effects of a high-altitude airburst with large electromagnetic pulse on the GPS satellite constellation or on GPS signal transmissions through the ionosphere. To include these factors in an analysis, we suggest using off-line analysis, similar to the ASAT analysis described above. Once the number of satellites that can still transmit signals to a region over time has been determined, the GPS state can be entered into the TLC/NLC model and the analysis performed.

Direct Threats Against Differential GPS Transmitters

Direct threats against ground-based differential GPS transmitters are much more likely than direct threats against the GPS satellites. Since the location of the differential GPS transmitters may be known to all parties before the conflict, and the fact that their transmissions can be detected, the life expectancy of such transmitters may be short if targeted by the enemy. Differential GPS transmitters that are destroyed or otherwise forced to cease operations are no longer capable of assisting assets in location accuracy.

It is difficult to prepare counter-countermeasures to differential GPS countermeasures. One method of defense is to proliferate the differential GPS transmitters in a field, rather than as only a point source. Each transmitter can be targeted and destroyed, but it is more difficult to take out the whole field.

In TLC/NLC, it should be sufficient to represent GPS transmitters as just another fixed target for purposes of attrition and suppression calculation. There is no need for additional model attributes, although the vulnerability of such transmitters should be obtained. A similar representation is adequate for differential GPS relay transmitters.

Direct Threats Against GPS Receivers

GPS receivers can also be targeted. However, since the GPS receivers tend to be contained in the asset, destroying the GPS receiver tends to destroy the platform as well. As a result, the normal attrition model in TLC/NLC should be adequate

[1] As mentioned before, INS-equipped assets are less affected by gaps in GPS reception if the gaps are less than one hour long for navigation purposes, or a few minutes for targeting purposes. Therefore, it may not be necessary to track changes in the GPS state that are less than 15 minutes long.

to address direct attacks against GPS receivers. The best counter-countermeasures to direct threats against GPS receivers are normal survivability measures.

Threats Against GPS Signals

We will discuss two types of threats against GPS signals: jamming and spoofing of GPS signals.

Jamming GPS Signals

Probably the most effective and most likely threat against GPS use will be jamming of the GPS signal. The GPS signal has a very low power (about 10^{-16}W) within a known (20 MHz) frequency range and therefore is susceptible to jamming. Even relatively small 10-W jammers can substantially degrade the GPS signal at a range of 20–40 km. More powerful jammers can substantially increase that range, albeit at the cost of increasing their signature to counter-threats.

If the jammers are transmitting in a narrow (much less than 20 MHz) frequency band, then the following countermeasure can be used. The software package on many of the receivers can detect a single frequency spike in amplitude well above the absolute GPS transmissions and then notch out (ignore) this narrow frequency band. As a result, the rest of the unjammed GPS frequency band is available for access by the receiver.

However, if the jammer fills the 20 MHz GPS band, notch filtering will be ineffective, and the entire band will be jammed. As a result, it will be difficult for the receiver to achieve and retain lock-on to the GPS transmissions, and it will lose the signal.

An alternative counter-countermeasure would be for the GPS receiver to use a directional antenna to ignore GPS jamming signals.[2] If the jammer is ground-based, it is possible for the receiver to ignore all signals that do not come from the sky. Unfortunately, it is much more difficult to avoid a jamming signal from an airborne platform. It is difficult for a platform to retain lock-on to the GPS signal

[2]Directional antennas help both airborne and ground-based GPS receivers. For example, if a ground-based jammer is attempting to jam ground-based GPS receivers, a directional antenna will help reduce the effects of jamming. Similarly, if an airborne jammer is attempting to jam a ground-based GPS receiver, it will be more difficult to counter the jamming strictly through the use of a directional antenna. Both ground-based receivers and jammers must be concerned about terrain masking of the signal they are trying to receive or jam. Terrain masking will not be explicitly considered in TLC/NLC, but will be included implicitly when the analyst defines regions of jamming as model inputs.

being jammed from the same general direction (see Frost and Schweitzer, forthcoming).

One of the best counter-countermeasures to jamming of GPS signals is to attack the jammers. Since jammers must radiate more or less continuously and at sufficient power to jam at long range, they are rather visible targets. As a result, a version of the antiradiation missile used against air defense radars could also be used against GPS jammers. Conversely, a shrewd opponent would place the GPS jammers at locations that would make it difficult for the United States to attack, such as populated places or other sites with a high potential for undesirable collateral damage. A near miss might disable the transmitter, but would increase the humanitarian cost.

If the enemy were to simply radiate jamming signals continuously from a single large transmitter, it would be relatively easy to locate and suppress that jammer. As an alternative, the enemy could attempt to proliferate a large number of small jammers to achieve the same effect. If there are a large number of low-power jammers in action in the same area, destroying the field of jammers will not be cost effective.

Conversely, it may not be cost effective for the enemy to proliferate GPS jammers to deny U.S. GPS access when compared with the opportunity cost of forgoing additional military capability for their side. For example, a 10-W jammer will consume a car battery's worth of power every four hours, which is an expensive opportunity cost for most regional threats.

In TLC/NLC, GPS jamming assets will need to be represented in the model. They can either be separate objects with their own state and attributes, or the ability to jam GPS can be an attribute of the target. It will probably be better to use the former representation, since it will be more readily included in the existing system of target objects.

In addition, TLC/NLC will need data on the effects of jamming by size and type of jammer and the effects on GPS receivers (by type) as a function of the range (see Table 5). Table 5 shows jammer effects on an absolute GPS receiver, or an absolute GPS receiver with nulling or notch-filter software, or an absolute GPS receiver with nulling software and a directional antenna. Note that Table 5 applies to only a single jammer or a few jammers, not a large number of low-power jammers.

The data should include distinctions between narrow-band and wide-band jammers, as well as ground-based and airborne jammers. Each of these jammers is more or less effective against software (a nulling or notch-filter) and directional

Table 5

Determination of Possible Jamming Effects

Type of Jammer	Type of Receiver (Air or Ground)	Effect of Jamming	Power Factor
Narrow-band ground	Absolute	Check for jamming	1.0
Narrow-band ground	Nulling software	Minimal effect	1.0
Narrow-band ground	Directional ant.	Minimal effect	0.033
Narrow-band air	Absolute	Check for jamming	1.0
Narrow-band air	Nulling software	Minimal effect	1.0
Narrow-band air	Directional ant.	Minimal effect	1.0
Wide-band ground	Absolute	Check for jamming	1.0
Wide-band ground	Nulling software	Check for jamming	1.0
Wide-band ground	Directional ant.	Minimal effect	0.033
Wide-band air	Absolute	Check for jamming	1.0
Wide-band air	Nulling software	Check for jamming	1.0
Wide-band air	Directional ant.	Check for jamming	1.0

antenna counter-countermeasures. This decrease in location accuracy will be translated into decreased lethality or decreased probability of reaching the target, as described earlier. Direct attacks against GPS jammers will be represented in the normal TLC/NLC attrition processes like any other fixed or mobile target.

If "Effect of jamming" is "Minimal effect," then normal target location accuracy calculations occur unless the jammer power is very large. If the table indicates "Check for jamming," then Table 6 determines the approximate range at which jamming takes place.

Table 6

Determination of Range of Jamming to Break Lock or Preclude Signal Acquisition[a]

Type Jammer to Type Receiver	Type User or Access[b]	Jammer Power (W)	Range (km) at Which Jamming Breaks Lock	Range (km) to Preclude Signal Acquisition
A-A, A-G, G-A	P-code	1	4.5	43
A-A, A-G, G-A	P-code	10	13.5	135
A-A, A-G, G-A	P-code	100	43	427
A-A, A-G, G-A	C/A code	1	13.5	120
A-A, A-G, G-A	C/A code	10	43	380
A-A, A-G, G-A	C/A code	100	135	1200

[a]Table assumes a P-code user, INS-aided platform, no anti-jamming enhancements, and a 0-dB difference in the gain to the jammer and to the satellite.

[b]Note that P-code requires about 10 times the jamming power to jam the signal at the same range as C/A code. If the power drops as the square of the range, then if 10 W can break lock against P-code at 13.5 km, it will jam C/A code at 3.16 times 13.5 km, or 43 km.

Table 6 determines the estimated range that a jammer with the indicated effective radiated power (transmitter power times antenna gain) could break a GPS receiver's lock on an already acquired GPS signal. This table also includes the range at which the GPS signal will not be acquired by a receiver as a function of the jammer power. Note that it takes more power to jam an already acquired GPS signal than it does to preclude the acquisition of a GPS signal.

If the jammer is ground-based and the receiver airborne, multiply the jammer's power by the power factor in Table 5. This factor accounts for the fact that a ground-based jammer attempting to jam a directional antenna (that is looking up) will require about 30 times as much power as an airborne jammer to achieve the same effect. The jammer power decreases roughly as the *inverse square* of the range due to minimal reflections (see Frost and Schweitzer, 1993), or

$$\text{received power} = \text{constant} * \text{jammer power}/(\text{range})^2 \qquad (5.1)$$

Note that these numbers apply only to jammers within line-of-sight of receivers, such as airborne jammers against ground receivers, airborne jammers against airborne receivers, and ground-based jammers against airborne receivers. In the case of a ground-based jammer against a ground-based receiver, there is additional attenuation from ground reflection, clutter, and the like, which causes the jammer power to decrease more quickly as a function of range after the first kilometer (see Analytic Sciences, 1976). Depending on the assumed environmental conditions along the transmission path, the decrease in power may be as much as the third or fourth power of the range. As a result, ground-based jammers tend to be relatively effective against P-code receivers either when the receivers are within 1 km of the jammer or in situations where the receiver must acquire lock-on while within jamming range, as in heavy foliage.

In TLC/NLC, we assume that air and naval platforms will tend to already have a GPS signal lock when encountering enemy jamming. As a result, the second to last column will be used to determine the effects of jamming. As mentioned in Section 3, foliage can preclude line-of-sight to the GPS signal. Therefore, jamming against ground units in foliage should use the last column in the table, since it is unlikely units in that environment will be able to maintain a continuous lock on the GPS signal. Therefore, ground units in heavy foliage are more susceptible to an enemy GPS jamming threat. In addition, all friendly units within one kilometer of enemy GPS jammers will be considered unable to maintain lock to the GPS signal.

Spoofing GPS Signals

Spoofing GPS signals is a method by which an opponent attempts to mimic the GPS signal, thereby misguiding the GPS receiver with false location data. A successfully spoofed GPS-guided munition will be directed away from the desired target.[3] It is possible to spoof C/A code, but the encrypted P-code (called the Y-code) is considered spoof resistant. Although P-code receivers are currently available only to U.S. military and other authorized users, the Y-code is a hedge against the time when a potential enemy has access to P-code receivers.

It is much more difficult to spoof a GPS receiver than to jam it. Because it takes four GPS satellites to adequately define a receiver's location in four dimensions, spoofing just one satellite is unlikely to allow the asset to be misguided significantly off course.

Owing to the complexity and uncertainty associated with GPS signal spoofing technology and techniques, we do not plan to explicitly represent this feature in TLC/NLC. We will consider likely spoofing sites (if any) as just another form of jammer with possibly different effectiveness parameters as a function of range and type receiver.

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[3]Most opponents will guide the weapon to explode in a harmless area. Ruthless opponents may try to guide the weapon into populated areas to increase collateral damage that could be blamed on the United States.

Bibliography

Allen, Patrick D., *Air Combat Model Engagement and Attrition Processes High Level Design*, N-3566-AF/A, RAND, 1993.

Analytic Sciences Corporation, *Investigation of Critical Issues for Army Users of the NAVSTAR Global Positioning System*, AFAL-TR-75-156, May 1976.

ARINC, *GPS NAVSTAR User's Overview*, ARINC Research Corporation, YEE-82-009D, March 1991.

Beser, J., and B. Parkinson, "The Application of NAVSTAR Differential GPS in the Civilian Community," *Global Positioning System Papers Published in Navigation Volume II*, The Institute of Navigation, Washington DC, 1984.

DOT/DoD, *Federal Radionavigation Plan 1992*, Department of Transportation and Department of Defense, DOT-VNTSC-RSPA-92-2, DOD-4650.5, 1992.

Frost, Gerald, and Bernard Schweitzer, "Operational Issues for GPS-Aided Precision Missiles," *1993 National Technical Meeting Proceedings*, The Institute of Navigation, Washington, DC, January 1993.

Frost, Gerald, and Bernard Schweitzer, *Operational Issues for GPS-Aided Precision Guided Weapons*, MR-242-AF, RAND, forthcoming.

Hillestad, Richard, Louis Moore, Eric Larson, *Theater-Level Campaign Model; Nonlinear Tool Kit: An Overview*, RAND, MR-180-AF/A, forthcoming.

Moore, Louis, *CADEM: Calibrated Differential Equation Methodology for Aggregate Attrition*, RAND, MR-170-AF, 1993.

Sweeny, Bruce D., Project Manager, Global Positioning System, briefing entitled "GPS Army User Equipment," June 1993.